Avionics

Pete Capizzo

X-Ray Surveyor Communications

- **Communications System Comparison:**
  - Following Chandra's downlink schedule of once every 8 hours, for 1 hour:
    - X-Ray Surveyor data of 240 Gbits/day gives 80 Gbits/8 hr to be downlinked.
    - 80 Gbits downlinked in 60 minutes requires a rate of 22.2 Mbps.
  - Using DSN 34m dish ground station parameters:
    - 54.0 G/T for X-Band and 65.7 G/T for Ka-Band
  - Using the Mercury Messenger like Phase Array antennas for science downlink:
    - with a gain of 24.7 dB for X-band and 26 dB for Ka-band.
  - Using LADEE LLCD 100nm Laser Comm system:
    - Assuming about 30 dB margin required with 30 dB atmospheric attenuation.

Conclusions for SEL2:

- X and Ka band PA systems will result in similar system mass, with Ka being slightly better.
  - PA size about 0.25m, 25 and 20 watt RF power required respectively.
- Laser comm system will be significantly lighter:
  - 10 cm aperture, 5 watt RF power
  - Optical/Laser communication on DSN should be available by 2025, but not guaranteed:

JPL/NASA, *Deep Space Network: The Next 50 Years*, Deutsch et al. FISO 8-10-2016

X-Ray Surveyor Communications

X-Ray Surveyor Communication System Trade Chart, for downlink rate of 22.2 Mbps

	Chandra Like Orbit	Margin	ESL2	Margin
Range	133,000 km apogee		1.5x10^6 km (0.01 AU)	
X-band Power	1 watt	10 dB	25 watt	3 dB
Ka-band Power	1 watt	12 dB	20 watt	4 dB
Optical Power	0.5 watt	40 dB	5 watt	30 dB

- At ESL2, minimum margin required is 3 dB for X and Ka band, 30 dB for optical assumed.
- In Chandra like orbit, the low power and high margins mean greater link rates can be achieved.
  - Over 100 Mbps at 1 watt RF.

GUIDANCE, NAVIGATION, & CONTROL

Alexandra Dominguez (EV41)
Chris Becker (EV42)
Brian Bae (EV41)
Dr. Bob Kinsey, ASC (2015 Study)
11/10/2016

Ground Rules and Assumptions

Requirement	Requirement (Goal)	
Launch Year	2030	
Spacecraft Lifetime	5 years	
Consumables	20 years	
Orbit	SE-L2, Chandra-type, LDRO, or Drift Away	
Orientation	Constant Inertial Pointing	
Fault Tolerance	Single-fault tolerant	
Pointing	Radial	Roll (boresight)
Accuracy	30 arcsec (3 sigma)	30 arcsec or better
Knowledge[1]	4 arcsec (pitch/yaw) RMS 99%	4 arcsec or better
Stability[2]	±1/6 arcsec per sec, per axis (3 sigma)	1/6 arcsec per sec or better
Dithering	Lissajous figure, up to +/- 30" amplitude with 8 bits resolution; periods 100 to 1000 seconds subject to derived rate constraint; arbitrary phase (8 bits: amplitude, rate and phase are to be independently commanded in yaw and pitch).	

1 Driven by ground reconstruction of pointing; looser knowledge could be adequate to support pointing accuracy.

2 A 100,000-second observation interval is made up of many short measurements, so short-term stability is the key.

General Mission Requirements

Requirement	Requirement (Goal)
Slew rates for normal observing (and #/day)	90 deg/30 minutes*, #/day is **<TBD>** (soft requirement that does not drive the design)
Slew rates for TOO** (and #/day)	1 TOO per week. Slew rates same as above.
Continuous	100000 s***
Avoidance angles	
Sun	45 degrees; but the rest of the sky must be accessible (this may affect the solar array articulation mechanisms)
Other	N/A (We aren't doing a sky coverage analysis, so only the sun avoidance angle will affect the design to first order)

*Not a primary driver for design. Suggested wheel configuration can support 27.6 minutes with 9.6% margin on wheel momentum capability or 35.8 minutes with 30.5% margin, for the worst slew axis.

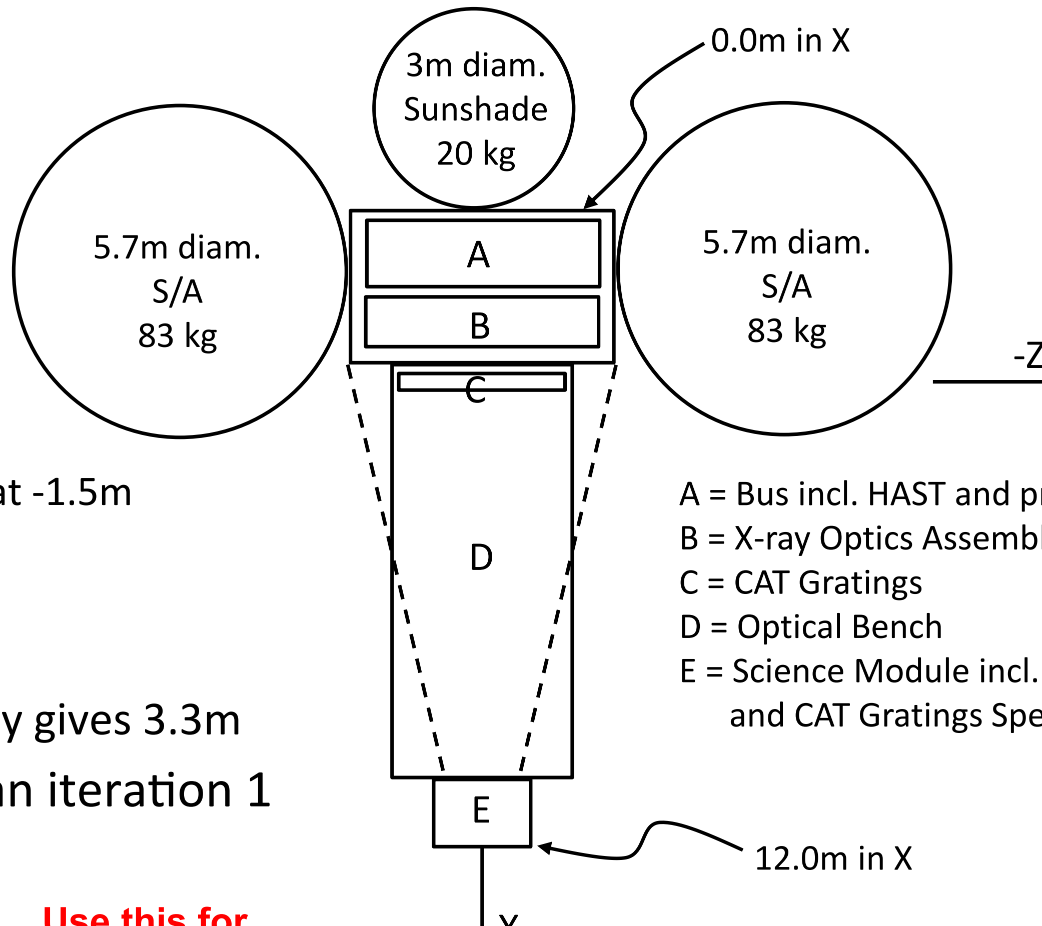
**Target of Opportunity: an unscheduled observation of interest, such as a sudden X-ray emission from an interstellar or intergalactic source.

***Can pause observation for momentum unloading if necessary. Suggested 6 for 8 wheel configuration provides capability to go for > 100,000 seconds without unloading.

Momentum unload and damping of rates due to orbital insertion/burn maneuvers assumed to be carried out using RCS/ACS thrusters. Required Delta V is accounted for in prop budget.

Mass Properties Estimate

- Inertias for Y, Z axes (⊥ to boresight) are key for determining wheel capability needed to support slew through 90 degrees in 30 minutes.
- Assumptions
  - Solid circular cylinders
    - A+B+C 4m diam. x 2.85m 4572 kg; CM at 1.43m in X
    - D 2.5m diam. x 8.15m 833 kg; CM at 6.93m
    - E 1 x 2 x 2m; 633 kg; CM at 11.5m
    - S/A CMs at 1m; Sunshade at -1.5m
- Total mass 6224kg
  - CM at 3.2m in X
    - Treating A,B,C separately gives 3.3m
  - Inertias a little larger than iteration 1
    - I_{XX} = 14,233 kg-m^2
    - I_{YY} = 87,961 kg-m^2 ← **Use this for wheel sizing**
    - I_{ZZ} = 83,945 kg-m^2



A = Bus incl. HAST and propellant
B = X-ray Optics Assembly
C = CAT Gratings
D = Optical Bench
E = Science Module incl. XMIS, HDXI, and CAT Gratings Spectrometer

Sensor and Actuator Info (1 of 3)

- Sensors
  - IMU: 3x Honeywell Miniature Inertial Measurement Unit (MIMU)
    - Uses GG1320 Ring Laser Gyro (RLG)
    - Range: +/- 375 deg/sec; Bias <= ±0.005 arcsec/sec (1 sigma)
    - Align the three IMUs so that no two gyro axes are aligned.
    - Operate two IMUs (6 gyros) at a time, so that gyro failure can be identified in real-time in software.

  - Star Tracker: Ball Aerospace HAST
    - ±0.2 arcsec per axis (1 sigma) while tracking at rates up to 1 degree/second[1]
      - RSS of random, spatial, and boresight errors
    - >94% success rate over 7 years
    - Derived from Chandra's Aspect Camera

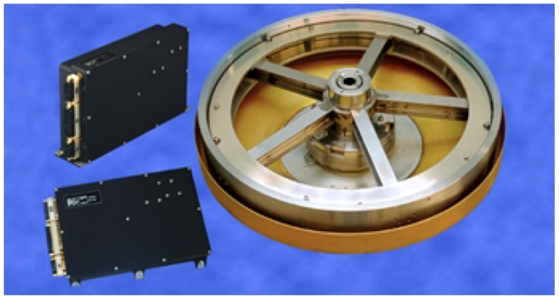
Performance Characteristics	
Random	0.110 arcsec 1 σ
Spatial	0.140 arcsec 1 σ
Boresight	0.100 arcsec 1 σ

  - Adcole Coarse Sun Sensors 2x
    - 2 Pi steradian FOV, accurate to a few degrees
  - Adcole Fine Sun Sensors 2x
    - Limited FOV (e.g., 64 x 64 degrees), accurate to a small fraction of a degree
  - Fiducial System (part of the Instrument) for knowledge of HAST relative to Telescope
    - Typically includes one or more lasers and a number of corner reflectors

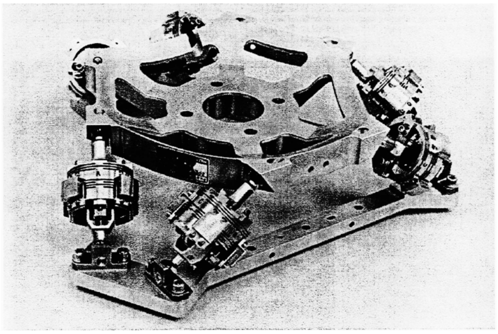
[1] Dan Michaels, James Speed, "New Ball Aerospace star tracker achieves high tracking accuracy for a moving star field," Acquisition, Tracking, and Pointing XVIII, edited by Michael K. Masten, Larry A. Stockum, Proceedings of SPIE Vol. 5430(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.549107, Downloaded From: http://proceedings.spiedigitallibrary.org/ on 06/17/2015

Sensor and Actuator Info (2 of 3)

- Actuators
  - Reaction Wheels: Rockwell Collins Teldix RDR 68-3
    - Each Wheel: Torque 0.075 Nm, Mom. Storage 68 Nms
    - 8 wheels in "pyramid" configuration; 6 of 8 in operation at a time
      - Cant angle and pyramid orientation can be optimized for more or less capability in any given axis
      - 338 Nms capability for pitch and yaw (perpendicular to boresight): axes with larger inertias, and slew axis will be in the pitch/yaw plane.
      - 106 Nms capability for roll (twist about boresight)



  - Reaction Wheel Vibration Isolation[1, 2]
    - One isolator per wheel; < 2 kg per isolator.
    - Northrop Grumman heritage design used on Chandra and JWST
      - Designed specifically for Teldix RDR 68 wheel
      - Could be modified for a different wheel with comparable mass if the Teldix wheel is not available for this mission
    - Does not require launch locks

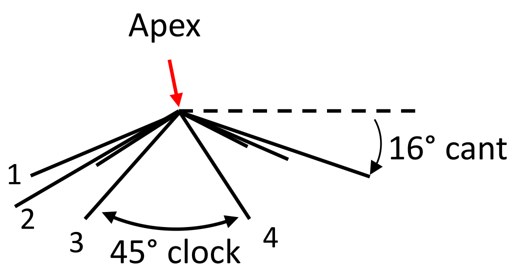


[1] Karl J. Pendergast, Christopher J. Schauwecker, "Use of a passive reaction wheel jitter isolation system to meet the Advanced X-ray Astrophysics Facility imaging performance requirements," SPIE Conference on Space Telescopes and Instruments V • Kona. Hawaii • March 1998, SPIE Vol. 3356 • 0277-786X/98, pp. 1078-1094.

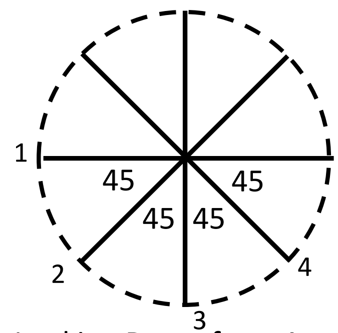
[2] Dr. Reem Hejal, Northrop Grumman, Dynamacist for Chandra, phone call on 19 June 2015.

Sensor and Actuator Info (3 of 3)

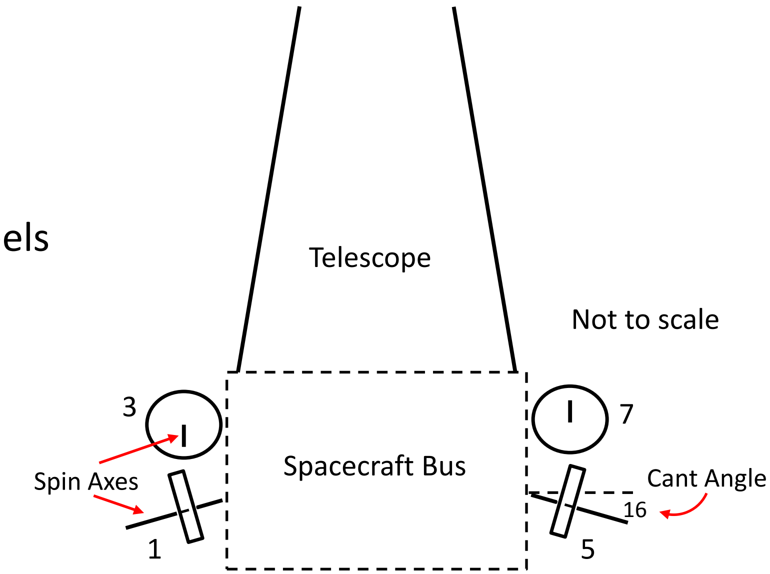
- Wheel Pyramid
  - Pairs of opposite wheels shown to the right
  - Spin axis cant angle ~16 degrees for each wheel
  - Spin axis clock angle of 45 degrees between adjacent wheels



3D View of Spin Axes

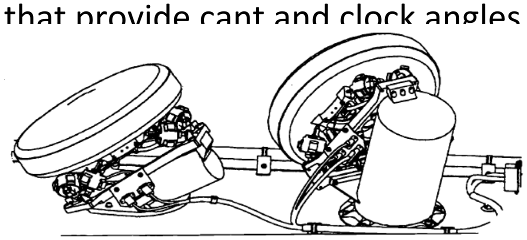


Looking Down from Apex

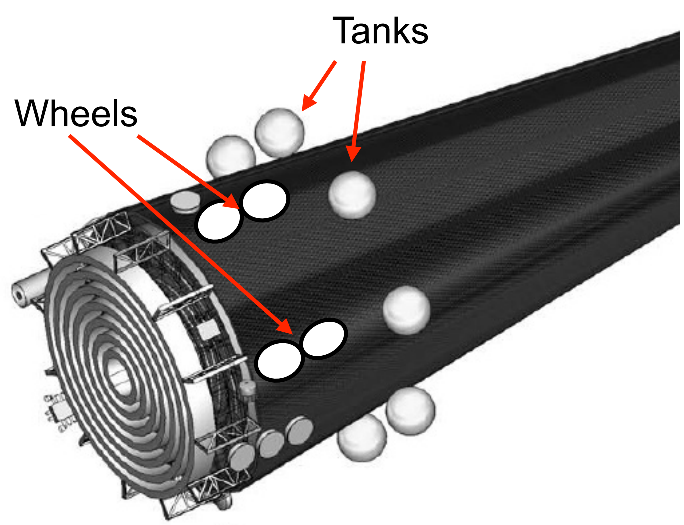


Opposite Pairs of Wheels

- Locations on the vehicle
  - Similar concept used for Chandra
  - Wheel pair at each of four locations
    - 90 degrees around barrel between pairs
  - Isolators mounted to standoffs that provide cant and clock angles



From reference 1 on the previous chart.



Slew Time

- Slew time for worst axis using 4 wheels after a wheel failure.
  - While operating 6 of 8 wheels, only 4 contribute for the worst axis.
  - 27.6 minutes to slew 90 degrees with 9.6% wheel momentum margin
    - 35.8 minutes to slew 90 degrees with 30.5% margin.
  - Recommend allowing 36 minutes for a 90 degree slew.
- Slew profile used for analysis: max torque to reach max wheel momentum, coast at max rate, then max torque to return to near zero wheel momentum.
- Minimum slew time

$$t = \frac{h}{\tau} + \frac{I\theta}{h}$$

- h = max momentum
- I = slew axis inertia
- θ = slew angle
- τ = max torque

Vehicle			Wheel Pyramid	
Y Inertia (kg-m2)	87961.0		Cant Angle (deg)	16.0
Z Inertia (kg-m2)	83945.0		Clock Angle (deg)	45.0
X Inertia (kg-m2)	14233.0			
			1-Wheel Max Slew Momentum (Nms)	68.0
Slew Angle (deg)	90.0		1-Wheel Max Torque (Nm)	0.075
Minimum Slew Time (min)	27.6		4-wheel multiplicative factor	2.72
Average Slew Rate (deg/sec)	0.054			
Max Momentum for Minimum Slew Time (Nms)	167.1		4-wheel Max Slew Momentum (Nms)	184.9
Margin using 4 Wheels (%)	9.6%		4-wheel Max Torque (Nm)	0.20
Max Momentum with 30% Slew Time Contingency (Nms)	128.5		Minimum Slew Time (min)	27.6
Margin using 4 Wheels (%)	30.5%		Slew Time with 30% Contingency (min)	35.8

Disturbance Environment (1)

Torque (Nm)	Candidate Orbit			
	CTO**	**SE-L2 Halo**	**LDRO**	**Drift Away**
Solar Pressure*	-6.2E-4	-6.2e-4	-6.2e-4	-6.2e-4
Gravity-gradient	3.9E-3	n/a	2.3E-6	n/a
Aero***	-3.4E-9	n/a	n/a	n/a
Magnetic	7.1E-7	n/a	n/a	n/a
Total	**3.3E-3**	**-6.2e-4**	**-6.2e-4**	**-6.2e-4**

**Gravity gradient, aero, and magnetic torques calculated at perigee (16,000 km)

***Mean atmospheric density, c_d=2

***Solar Torque Calculation (Solar Constant at 1AU, orientation 45° to Boresight)**
(Most stressing case- high CP-CM offset)

	PCM (m)	Area (m^2)	Angle Rel to Sun (deg)	Angle Rel to Sun (rad)	Frontal Area (m^2)	Reflectance	Force (N)	Torque (Nm)
Sunshade	-4.8	7.1	90	1.570796327	7.1	0.7	5.4999E-05	-0.000263995
Solar Arrays	-2.3	51	90	1.570796327	51	0.3	0.000302107	-0.000694846
Spacecraft Bus and Star Tracker	-2.4	8.1	45	0.785398163	5.727564928	0.7	4.43676E-05	-0.000106482
X-ray Optics Assembly	-1	4.725	45	0.785398163	3.341079541	0.7	2.58811E-05	-2.58811E-05
Optical Bench Assembly	3.6	18.75	45	0.785398163	13.25825215	0.7	0.000102703	0.00036973
XMIS, HDXI, and CAT Graing Spectrometer	8.2	2.25	45	0.785398163	1.590990258	0.7	1.23243E-05	0.00010106
Totals		91.925			82.01788687		0.000542382	**-0.000620415**

Disturbance Environment (2)

Torque (Nm)	Candidate Orbit			
	CTO**	SE-L2 Halo	LDRO	Drift Away
Solar Pressure*	-6.2E-4	-6.2e-4	-6.2e-4	-6.2e-4
Gravity-gradient	3.9E-3	n/a	2.3E-6	n/a
Aero***	-3.4E-9	n/a	n/a	n/a
Magnetic	7.1E-7	n/a	n/a	n/a
Total	3.3E-3	-6.2e-4	-6.2E-4	-6.2e-4

**Gravity gradient, aero, and magnetic torques calculated at perigee (16,000 km)
***Mean atmospheric density, c_d=2

Most stressing case in terms of disturbance environment for Chandra Type Orbit is away from perigee where solar pressure torque is not partially cancelled out by other disturbance torques.

Momentum Storage

- Momentum accumulated in 100,000 s of Continuous Observation Time.
  - Can pause observation for momentum unloading if necessary. Suggested 6 to 8 wheel configuration provides capability to operate for > 100,000 s without unloading.

Candidate Orbit	Momentum Due to Disturbances (Nms)	Margin**
CTO	62.0	66.5 %
SE-L2 Halo	62.0	66.5 %
LDRO	62.0	66.5 %
Drift Away	62.0	66.5 %

**4-wheel (worst-case after a failure) max momentum = 184.9 Nms.

GN&C MEL

Component	Qty	Unit Mass (kg)	Total Mass (kg)	Contingency	Predicted Mass (kg)
Sun Sensor-Coarse	2	0.13	0.26	30%	0.34
Sun Sensor-Fine	2	2.00	4	30%	5.2
Star Tracker (2 heads, redundant elect.)	1	42.20	42.2	30%	54.9
Inertial Measurement Unit	3	4.50	13.5	30%	17.6
Reaction Wheels	8	7.60	60.8	30%	79.0
Reaction Wheel Drive Electronics	8	1.25	10	30%	13.0
Reaction Wheel Isolation Assembly	8	2.00	16	30%	20.8
Fiducial System (part of Instrument)	1	10.00	10	30%	13.0
				Total	**203.8**

- Could use lower contingency (e.g., 10% or less) for all but the fiducial system
  - Sensors, actuators, isolators are all TRL 9.
  - Mass savings using 10% contingency would be 29.4 kg predicted mass.
- Keeping 30% contingency allows for possibility that existing components might not be available for this mission.
  - Reasonable approach at this early stage of concept design.

Additional Actuator Options

- Survey of available reaction wheels for this type of mission - no official baseline configuration at this time.
- Assuming 4 wheel pyramid configuration for actuators – 4 wheel multiplicative factor = 2.72
- Desired slew rate: 90° in 30 minutes

Manufacturer[1]	Model	Unit Mass (kg)	Unit Peak Power (W)	Unit Average Power (W)	Unit Momentum (N-m-s)	Unit Output Torque (N-m)	Total Momentum using 4 Wheels (N-m-s)	Total Output Torque using 4 Wheels (N-m)	Dimensions (cm)	Missions/Built for Flight
Rockwell Collins	TELDIX RDR 57-0	7.6 + 1.45 (electronics)	90	20	57	0.09	**155**	**0.24**	34.5 dia x 11.8 (electronics not included)	Satellites 1500-5000 kg
Rockwell Collins *	TELDIX RDR 68-3	7.6 +1.25 (electronics)	90	20	68	0.075	**184.9**	**0.2**	34.5 dia x 11.8 (electronics not included)	Satellites 1500-5000 kg
Rockwell Collins	TELDIX MWI 100-100/100	16.5	300	35	100	0.1	**272**	**0.27**	30.0 dia x 15.0 (with electronics)	Not provided
Honeywell	HR-14-75	10.6	195	Not provided	75	0.4	**204**	**1.09**	36.6 dia x 15.9 (with electronics)	Many
Honeywell	HR-16-75	10.4	195	Not provided	75	0.4	**204**	**1.09**	41.8 dia x 17.8 (with electronics)	Many
Bradford Engineering	W45	6.95	64	17	20-70	0.3	**54.4-190.4**	**0.82**	36.5 dia x 12.3 (electronics not included)	Olympus, SOHO, Radarsat, Seastar, Skynet-4, XMM, Integral, Rosetta, ADM-Aeolus

* Selected in original study.

[1] Luke Rinard, Erin Chapman, Andrei Doran, Marc Hayhurst, Michael Hilton, Robert Kinsey, Stephen Ringler, "Reaction Wheel Supplier Survey Aerospace Corporation Report, January 6, 2011.

Recommendations / Future Work

- Update estimates of inertias, geometry, and disturbance environment as the spacecraft configuration is determined.
- Trade on vehicle rapid response
  - Consider representative observation sequences to better model momentum accumulation.
- Carry out in-depth dithering analysis.
- Develop system model to design and analyze controller performance
- Determine what the fiducial system needs to include.
  - Consider component placement.
  - Update the MEL.

Mechanisms

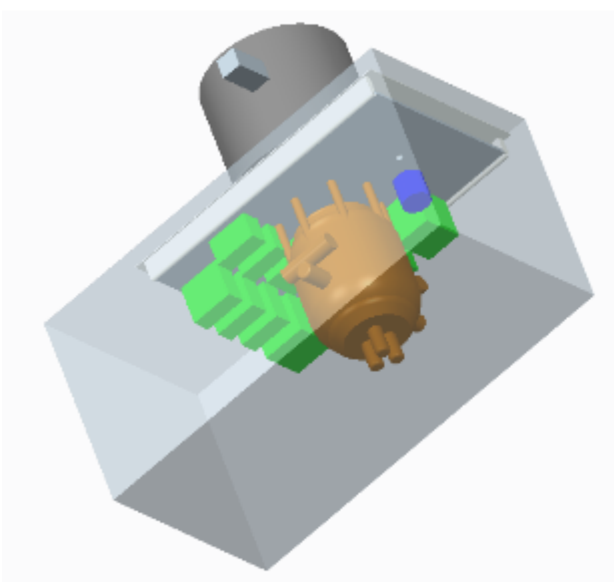
Alex Few

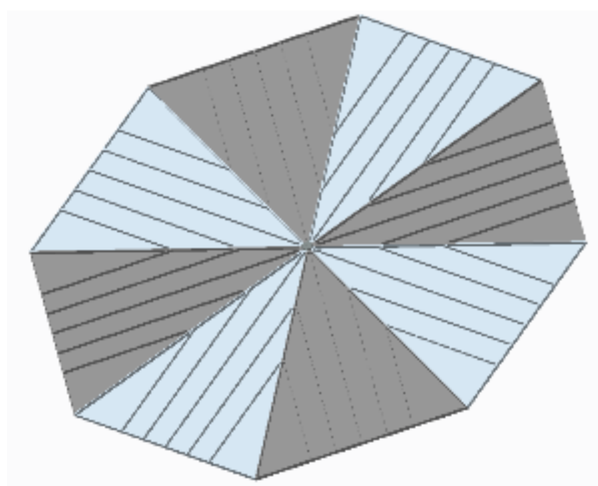
Mitchell Rodriguez

Justin Rowe

Mechanisms Studied

- Translation Table
  - Lateral Motion
  - Vertical Motion
- Inner Optics Door
- Outer Optics Door/Sunshade
- CAT Grating





ADVANCED CONCEPTS

Translation Table

- GR&A

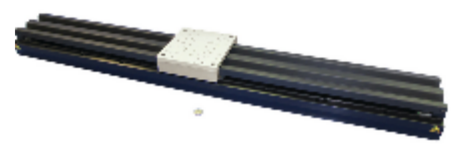
Category	Value
Instruments' focal plane location	WFI, X-Ray Calorimeter and CAT grating planes will be coplanar
CAT Grating Location	Not required on Translation Table
Horizontal translation accuracy	0.0002"
Vertical Translation distance	0.4"
X-Ray Calorimeter instrumentation locations	All instruments (coolers, power, etc) requiring to be less than 1 meter from Dewar Assembly will reside on the Translation Table
Enclosure	Translation Table, science, and supporting instruments will be fully enclosed
Launch Locks	Used until science is activated

Translation Table

- Approach and Tools
  - Direct Drive system (no power transfer via chains, belts, or gearing) is chosen due to extensive application in precision translation devices, accuracy, durability, and heritage success
  - Translating instruments are researched to verify that translation distance and, precision, and accuracy requirements could be mutually satisfied
  - If all requirements are satisfied by a commercial item, then it is assumed that the technology could be modified for flight
    - Vendors will produce specialty items to satisfy off gassing, loads, and reliability requirements
    - Price increase 10x to be expected
  - If no commercial item exists, then heritage flight hardware with similar application is examined and resized

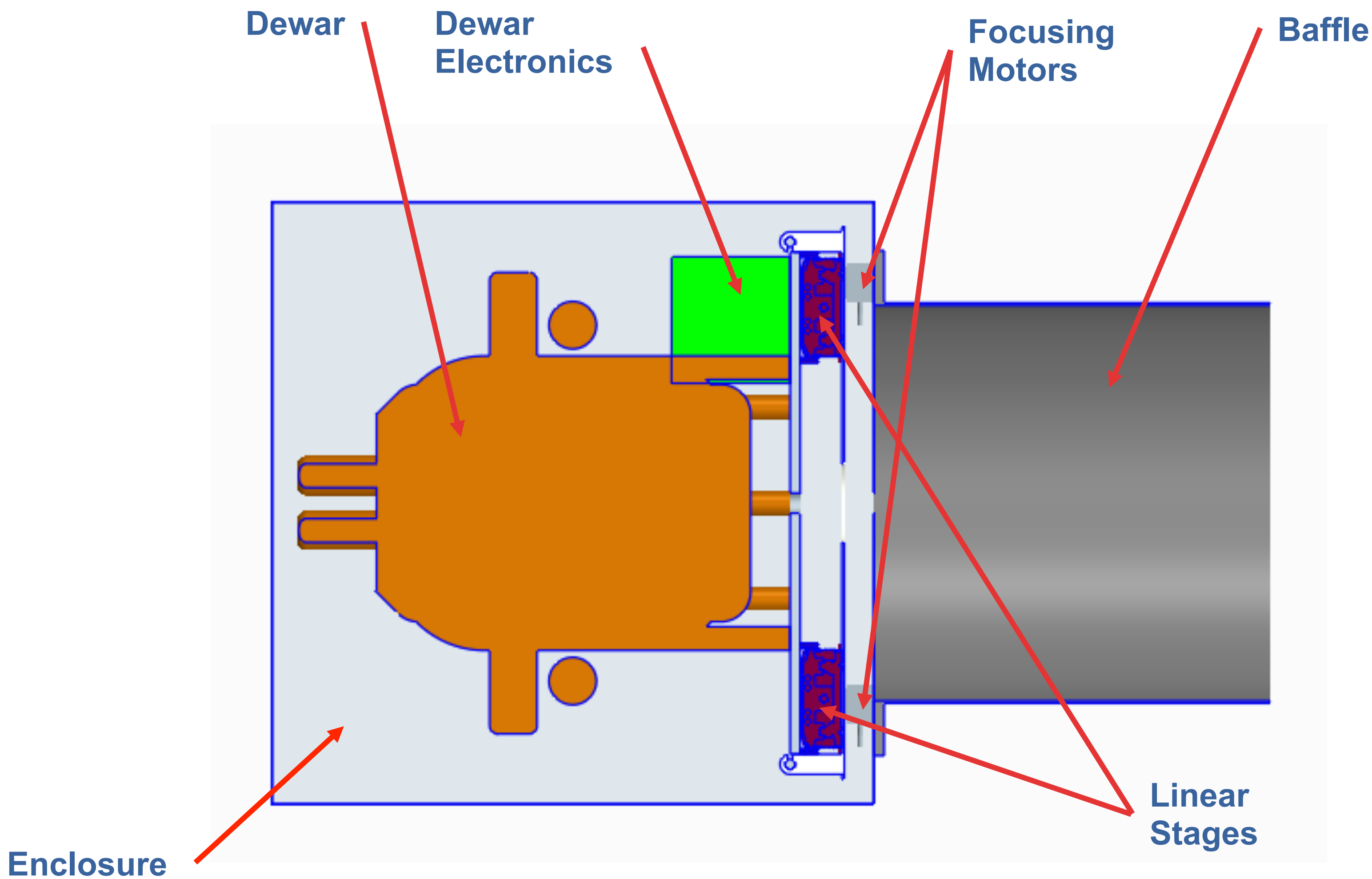
Translation Table

- Horizontal Translation Results
  - Direct Drive Linear Stage
    - These systems specialize in precision applications and are low-profile
    - Newport and Rockwell Industries produce applicable technologies with products within or near the accuracy and precision requirements
    - Launch locks will be required, unless product is modified for science mass under launch dynamic conditions
- Sizing Results
  - 750mm minimum translation required
  - 2 stages suggested due to table size
    - Reduce induced moments from acceleration
    - Redundancy
    - Commercial versions weigh about 30 kg
- Recommendations and Future Work
  - Contact manufacturers with questions regarding increasing product's accuracy, and certifying mechanism for flight



Translation Table

- Vertical Translation Results
  - Precision Vertical Stage
    - These systems are used in clean room or lab environments for optical applications
    - Meets translation and accuracy requirement
    - Commercial version uses roller bearings
    - Launch locks will be required, unless product is modified for science mass under launch dynamic conditions
    - Servos can be applied to commercial version
- Sizing Results
  - 1.2” (30 mm) translation
  - 4 stages suggested due to table size
    - Each commercial version weighs 3.3 kg
    - Each commercial version is 130 mm tall
- Recommendations and Future Work
  - Contact manufacturers with questions regarding increasing product’s accuracy, and certifying mechanism for flight


Dewar
Dewar Electronics
Focusing Motors
Baffle
Linear Stages
Enclosure

Inner Optics Door

- GR&A

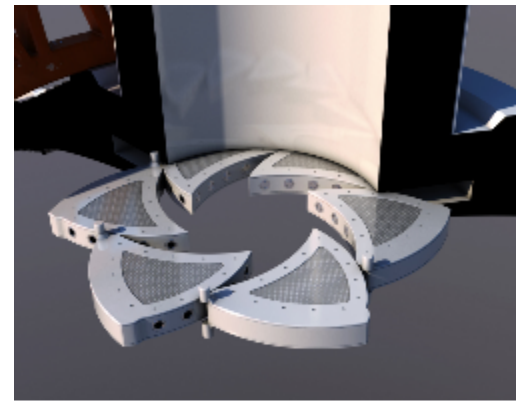
Category	Value
Service Life	Single use
Pressure	Pressure in Optics compartment, leakage allowed
Open/Closed position	Opened door must reside within optical bench and outside of optical path
Door position monitoring	Secondary monitoring device will be used (Chandra Heritage)
Material	Composite or Metallic

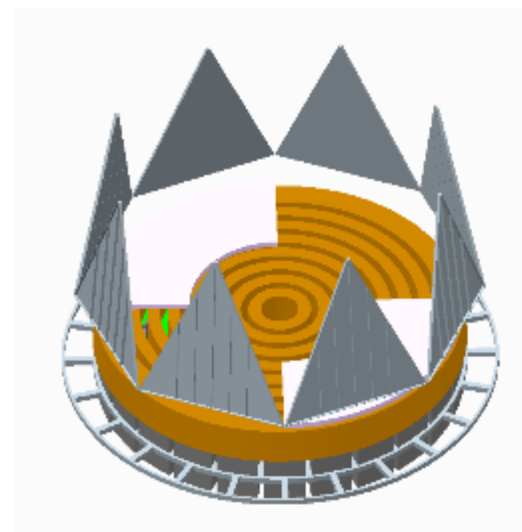
- Approach and Tools
  - The door must be over 3 meters in diameter and support launch loads as well as any loads created by pressure gradients
  - Mechanisms and structure must support all expected launch and pressure loads with a 1.4 margin of safety
  - Adequate containment of inert gasses and debris protection can be provided by either carbon fiber or grid-stiffened aluminum petals

Inner Optics Door

- Trades

Iris Door	Petalled Door
Low profile in direction parallel to optical path	More petals allow for lower profile in optical path
Requires much complex support structure, most likely extending outside of optical bench	Simper design
Limited application at this scale	Will require multiple mechanisms
	Will require door locks to support pressure





- Results
  - Octagonal door with petals
- Sizing Results
  - 8 equal-size petals with individual servos
  - 1/32"-1/16" thick with stiffeners
  - Door mass: ~80 kg
  - 8 single-use steppers and support structure: ~10 kg total

Inner Optics Door

- Recommendations and Future Work
  - Perform a trade between a metallic and composite door
  - Perform FEM analysis on door assemblies to better estimate masses

Outer Optics Door/Sunshade

- GR&A

Category	Value
Service Life	Single use
Pressure	Pressure in Optics compartment, leakage allowed
Open/Closed position	Opened door must open beyond optical path and serve as sunshade
Door position monitoring	Secondary monitoring device will be used (Chandra Heritage)
Material	Composite or Metallic

- Approach and Tools
  - Similar loads to Inner door to be expected
  - Mechanisms and structure must either support this load or be fixed by separate locking mechanisms
- Results
  - Stepper motors suggested
  - Reliable, well known technology
  - Higher holding torque than servo motor

Outer Optics Door/Sunshade

- Sizing Results
  - 2 stepper motors
    - Mass with support structure: 5 kg
  - Sun Shade Mass: 20kg est.
- Recommendations and Future Work
  - Contact Sierra Nevada or similar company for exact sizing for application

CAT Grating

- GR&A

Category	Value
Operation range	Grating must swing into and out of optical path multiple times
Position during launch	Stowed
Accuracy and precision	Large alignment tolerances
Neighboring structure and mechanisms	Inner door will remain outside of operation range
Door position monitoring	Secondary monitoring device will be used (Chandra Heritage)
Grating size	4 Sections covering 3000 cm^2 (about half of optic area)

- Approach
  - Gratings appear to be moderately sized, and loose tolerances will allow for less precise motion
- Results
  - 4 Compact Linear Actuator
  - Moog, Schaeffer Magnetics Division

CAT Grating

- Sizing Results
  - 3” of motion
  - 110 N output
  - 2.5 kg each
  - Heritage (UARS)
- Recommendations and Future Work
  - Obtain detailed design of CAT grating so that mass and inertia can be understood, resize actuator as needed